

Potential climatic and elevational range shifts in the Italian narrow endemic *Bellevalia webbiana* (Asparagaceae) under climate change scenarios

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Academic editor: Stefano Chelli | Received 4 August 2022 | Accepted 4 October 2022 | Published 8 November 2022

<https://zoobank.org/4E67DB34-D698-4DD6-9D64-28D683A50109>

Citation: Peruzzi L, Dolci D, Chiarucci A (2022) Potential climatic and elevational range shifts in the Italian narrow endemic *Bellevalia webbiana* (Asparagaceae) under climate change scenarios. Nature Conservation 50: 145–157. <https://doi.org/10.3897/natureconservation.50.91265>

Abstract

The Webb's hyacinth (*Bellevalia webbiana* Parl., Asparagaceae) is an Italian narrow endemic species, listed as Endangered (EN A2c) in the IUCN Global Red List of Threatened Species. The range of this bulbous perennial herb is restricted to two disjunct areas of Central Italy, separated by the mountain ridge of Northern Apennine. To evaluate the impact of climate change on this species, we used Ecological Niche Modelling (ENM) to predict future potential distribution under different scenarios, through Maximum entropy algorithm. The estimated potential distribution highlights the vulnerability of Webb's hyacinth to the effects of climate change. The current potential Area Of Occupancy (AOO) (992 2×2 km cells) is forecast to dramatically decrease in the range 2041–2100, under the scenarios SSP3-7.0 (2070 = –249, 2100 = –682) and SSP5-8.5 (2070 = –372, 2100 = –948). In all future scenarios, the predicted potential distribution shifts towards higher elevations, located in the two main areas in which the species currently occurs. This could imply a loss of the current genetic differentiation documented at the population level. To overcome these problems, in addition to assisted colonization, an *ex situ* conservation programme should be planned.

Keywords

Area of occupancy, climate change, conservation, endangered, Environmental Niche Modelling, Maxent, potential distribution

Introduction

Although soil consumption is a major concern for plant conservation, climate change caused by human activities can further exasperate conservation problems (Corlett 2016, 2020). Climate change is already impacting biodiversity and is likely to intensify over the next century (Bellard et al. 2012; Casazza et al. 2014), so that mitigation efforts are urgent to implement. In the case of species endemic to a country, the global chance of survival entirely relies on national policies, so that endemic taxa are key elements for setting national conservation priorities and for assigning conservation tasks (Orsenigo et al. 2018). Italy hosts a high number of endemics, between 19% and 21% of the native flora according to different estimates (Peruzzi et al. 2014, 2015; Bartolucci et al. 2018, 2022), and most of them show a quite restricted distribution range.

The Webb's hyacinth (*Bellevalia webbiana* Parl., Asparagaceae, monocots; Fig. 1) is one of the most relevant Italian narrow endemic species (Chiarugi 1949; Borzatti von Loewenstern et al. 2013; Astuti et al. 2017). The distribution range of this bulbous perennial herb is restricted to two relatively small and disjunct areas of Central Italy, separated by the mountain ridge of Northern Apennine. Despite the small distribution range, this species is linked to relatively common habitat types, since it typically grows in open fields and meadows, wood margins, olive groves, and vineyards (Gestri et al. 2010). Recent studies investigated the population genetics (Peruzzi et al. 2021), functional traits (Astuti et al. 2019), and reproductive performance (Astuti et al. 2018) of the five largest populations known for this species. These studies highlighted some differentiation in the population located at the upper NE limit of the species range, around Faenza (Ravenna). The International Union for Conservation of Nature (IUCN) listed the Webb's hyacinth in the Red List of Threatened Species (Peruzzi and Carta 2011; see also Orsenigo et al. 2018), as Endangered (EN A2c). During the last century, the main threat to this species was represented by the spread of human settlements, which caused local extinctions from several historical localities (Gestri et al. 2010). Climate change can quickly become a further threat for the persistence of the small and localised populations of this species, magnifying its extinction risk in the near future (Casazza et al. 2021). Therefore, to evaluate the impact of climate change on the conservation of *Bellevalia webbiana*, we modelled its future potential distribution under different scenarios by using Ecological Niche Modelling (ENM) (Khanum et al. 2013; Assis et al. 2018).

Methods

Occurrence data and study area

Distribution data for *Bellevalia webbiana* were obtained from Gestri et al. (2010), and from numerous recent field observations stored in Wikiplantbase #Italia (Peruzzi et al. 2019 onwards). A total of 122 distribution records retrieved from the above-mentioned sources were then filtered to retain only occurrence records in a 1×1 km grid cell. After filtration, 53 1×1 km grid cells remained for modelling the distribution



Figure 1. Webb's hyacinth (*Bellevalia webbiana*): general habit of the plant in flower from Vaglia, loc. Pratolino (Firenze), March 25, 2017 (left); detailed distribution expressed as 1×1 km grid cells and its localisation in Italy, North is upwards (right).

of the target species (Fig. 1). The study area was selected based on the known range of the species, corresponding to two relatively small and disjunct sites of Central Italy. This territory, located inside longitude 10.99–11.94 E and latitude 43.65–44.39 N (Fig. 1), covers an area of 3,192.37 km² and is characterised by a large absence area in correspondence of the Apennine mountain ridge, along the direction NW-SE.

Current and future climatic data

Mean monthly climatic data at the same 1 km² grid cell used for the occurrence data were downloaded from CHELSA (Karger et al. 2021) for three temporal ranges (1981–2010 'current times', 2041–2070, and 2071–2100). The climatic data were used to calculate three biologically relevant climatic variables (annual mean temperature, annual precipitation, and annual potential evapotranspiration) with *dismo* and *envirem* R packages (Hijmans et al. 2017; Title and Bemmels 2018; Dolci and Peruzzi 2022). Future climatic scenarios were derived from IPSL-CM6A-LR climatic models (Boucher et al. 2020) and related to three Shared Socioeconomic Pathways (SSP): SSP1-2.6 (CO₂ emissions cut to net zero around 2075), SSP3-7.0 (CO₂ emissions around current levels until 2050, then falling but not reaching net zero by 2100), and SSP5-8.5 (CO₂ emissions triple by 2075).

Ecological niche modelling

An ensembled method approach (Araújo and New 2007) was selected to calculate all potential distributions. Maximum entropy algorithm implemented in Maxent soft-

ware (version 3.3.4) (Phillips et al. 2022) and run via ENMtools (Warren et al. 2021) was used to calculate 100 models. Each model was calibrated randomly splitting the occurrence data in two subsets: 70% of for training and the remaining 30% for testing the predictive performance. Bootstrap was selected as replicated run type because it provides accurate inferences when sample size is small (Freedman 1981; Chen et al. 2019). Other parameters were kept as the default (regularization multiplier = 1, feature class combinations defined on the number of samples) (Merow et al. 2013). Model quality was assessed with two different evaluation metrics: the Area Under the Receptive Curve (AUROC) and the Continuous Boyce Index (CBI) (Hirzel et al. 2006). The CBI score provides valuable information on the model's quality (robustness, probability of occurrence and deviation from randomness) and is the most appropriate accuracy metric in the case of presence-only data (Hirzel et al. 2006). Albeit AUROC was considered the standard method to assess the accuracy of predictions, several drawbacks have been reported when applied to species distribution modelling (Lobo et al. 2008). Consequently, in this study, AUROC is reported just as complementary information.

The final ensemble maps were constructed by averaging all models in which CBI value calculated with testing subset was equal to or greater than 0.8. In total, predictions generated by 24 models were used to calculate mean habitat suitability maps together to the relative uncertainty maps.

To avoid extrapolation errors (Owens et al. 2013), and to enhance environmental similarity between the calibration and projection regions, the models were calibrated on the area within longitude 6.2–19.1 E and latitude 35.5–47.3 N. Only three non-collinear and biologically meaningful climatic variables were used as predictors (Barbet-Massin and Jetz 2014). All habitat suitability maps were converted to binary presence-absence outputs by applying a threshold value based on equal training sensitivity and specificity (Liu et al. 2005). Variable importance was computed by using the feature importance ranking measure (FIRM) approach (Greenwell et al. 2018; Scholbeck et al. 2019).

Geographic range estimation

The Area of Occupancy (AOO) as defined by IUCN Red List (IUCN Standards and Petitions Committee 2022) was used to assess extinction risk under the impacts of climate change. Accordingly, to estimate the potential AOO for future scenarios, all predicted potential distributions were downscaled to 2×2 km grid cells (IUCN Standards and Petitions Committee 2022) and the number of cells corresponding to predicted areas of potential presence was calculated.

Uncertainty estimation

The model replications allow to estimate the uncertainty associated with predictions. For each future scenario, all habitat suitability maps used to generate the ensemble prediction were also used to calculate variability as standard deviation. Then, the overall quality of predictions was evaluated by reporting values of uncertainty versus habitat

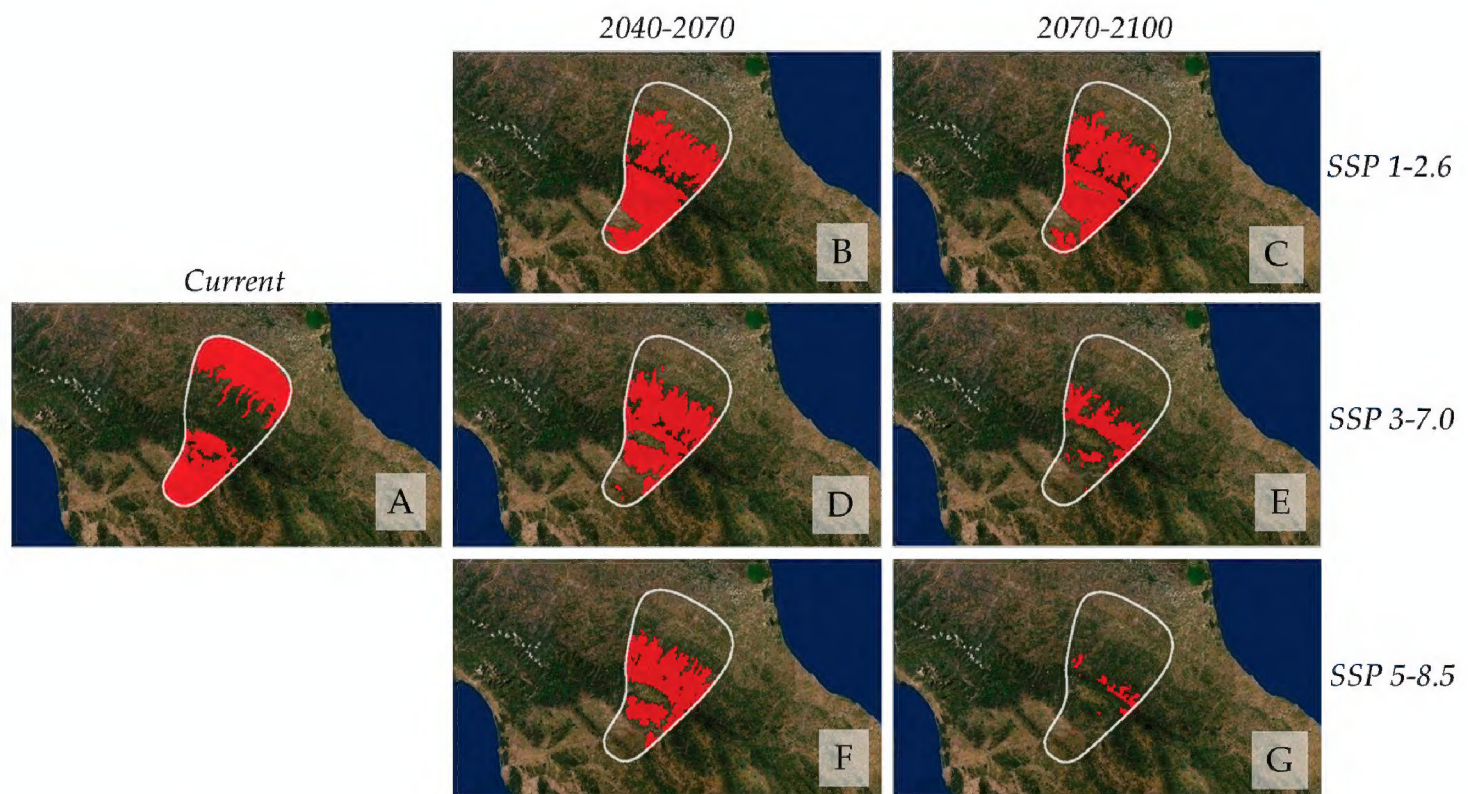


Figure 2. Predicted potential distribution for *Bellevalia webbiana* under current and future climatic scenarios. Cells potentially suitable for the species are highlighted in red, while the circumscribed study area is enclosed by the white line **A** current climatic condition **B** SSP1-2.6 scenario for 2040–2070 **C** SSP1-2.6 scenario for 2070–2100 **D** SSP3-7.0 scenario for 2040–2070 **E** SSP3-7.0 scenario for 2070–2100 **F** SSP5-8.5 scenario for 2040–2070 **G** SSP5-8.5 scenario for 2070–2100.

suitability in a 2D-scatter plot. Key areas are those showing high or low suitability and low uncertainty (Peterson and Samy 2016), corresponding to areas in which a species can be retrieved or not with a high degree of confidence.

Results

The ensembled Maxent model for the Webb's hyacinth with the selected environmental variables performed particularly well, achieving high evaluation metric scores ($AUC_{Train} = 0.932$, $AUC_{Test} = 0.928$, $CBI_{Test} = 0.853$). In total, 24 single models were combined into a final ensembled model. The current potential Area Of Occupancy (AOO), made up by 992 2×2 km cells, is forecast to decrease in the range 2041–2100 (Fig. 2).

The SSP1-2.6 scenario highlights limited variations in potential AOO (2070 = –11 potentially occupied cells, 2100 = –95). On the other hand, both SSP3-7.0 and SSP5-8.5 highlight a dramatic reduction of the potential AOO (SSP3-7.0: 2070 = –249, 2100 = –682; SSP5-8.5: 2070 = –372, 2100 = –948) (Table 1).

The feature importance ranking measure (Table 2) points out the great importance of Annual Mean Temperature and Annual Potential Evapotranspiration as predictors, even if Annual Precipitations also give a relevant contribution.

The overall uncertainty of predictions for current climatic condition (Fig. 3), calculated as a range of values, indicated a low level of uncertainty among replicated runs.

Table 1. Estimated values of potential Area of Occupancy (AOO) for *Bellevalia webbiana* calculated under current and future climatic scenarios.

Scenario	AOO (km ²)	number of 2×2 km cells	Δ of cells
Current	3,968	992	n/a
SSP 1-2.6_2070	3,924	981	-11
SSP 1-2.6_2100	3,588	897	-95
SSP 3-7.0_2070	2,972	743	-249
SSP 3-7.0_2100	1,240	310	-682
SSP 5-8.5_2070	2,480	620	-372
SSP 5-8.5_2100	176	44	-948

Table 2. FIRMs (Feature Importance Ranking Measure) showing the relevance of each variable in explaining the potential distribution of *Bellevalia webbiana*.

Variable	Importance	SD
Annual Mean Temperature	0.208	0.025343
Annual Precipitation	0.07	0.022094

The mean value of uncertainty for cells showing low and high habitat suitability (< 0.25 and > 0.75) was equal to 0.071 and 0.121, respectively. This indicates a high stability of predictions in the most relevant habitat suitability range. The mean value of uncertainty for cells showing intermediate habitat suitability (0.25 < suitability < 0.75) was equal to 0.216, higher but still low. The analysis of uncertainty for future projections returned results very similar to those calculated with current climatic conditions (not shown).

Discussion

We modelled the potential changes in distribution range of the Italian narrow endemic *Bellevalia webbiana* under different climate change scenarios, highlighting a significant reduction in its potential area of occupancy. This confirms the estimations made by Casazza et al. (2021), albeit carried out with a different focus and scope. These authors calculated that the assisted colonization of 13–16 new 2×2 km grid cells would be required to halt the estimated loss of range under a pessimistic scenario.

Several authors already evidenced similar future reductions in other stenochorous endemic plant species (Hong-Wa and Arroyo 2012; Wulff et al. 2013; Dülgeroğlu and Aksoy 2019; Khajoei Nasab et al. 2020; Semu et al. 2021), building up a consolidated body of knowledge on the potential risk of climate changes for the conservation of endemic plant species in different biogeographical contexts. The results of this study also reinforce the findings by Walker (2014) and Darrah et al. (2017), who highlighted the high risk of extinction of bulbous monocots, which often have stable local populations but limited dispersal capacity. In addition, the same authors remarked on the general underrepresentation of geophytes in plant conservation projects.

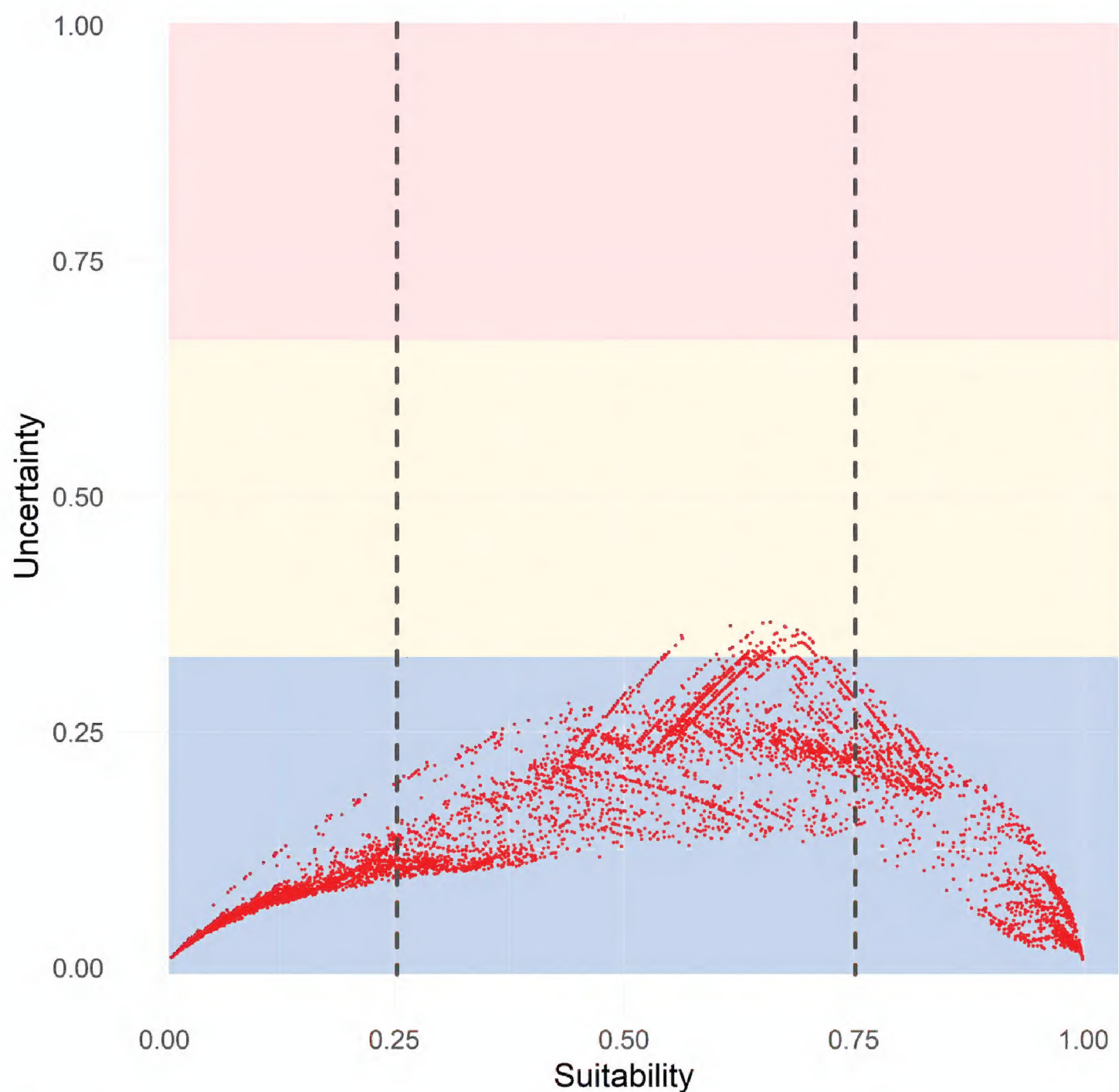


Figure 3. Plots of model uncertainty calculated as range of values observed across 24 replicate analyses in modelling the potential distribution of *Bellevalia webbiana* under current climate conditions. The values of uncertainty (y axis) were plotted against those of habitat suitability (x axis). Dashed lines delimit key areas for which habitat suitability can be associated with absence or presence with a high degree of confidence. Red, yellow, and blue areas of the scatter plot are associated with high, intermediate or low values of uncertainty.

In all future scenarios, the predicted potential distribution tends to shift towards higher elevations, which are located between to the two main areas in which this species currently occurs, but where this species is currently absent for other extra-climatic ecological reasons. We highlight that the Webb's hyacinth typically occurs at low elevations (on average ca. 200 m a.s.l.). Despite this, we predicted a tendency to shift towards higher elevations, as already evidenced for many species (Randin et al. 2009; Feng et al. 2020). Several other studies returned similar results, but concerning montane plants (Dirnböck, et al. 2011; Engler et al. 2011; He et al. 2019). In addition,

important resurvey studies of historical data demonstrated the upslope shift of several species, resulting in a complete transformation of the local assemblages in the same mountain range (Morueta-Holme et al. 2015; Steinbauer et al. 2018).

However, the upslope shift here modelled for *Bellevalia webbia* and the connected reduction in potential area of occupancy is only predicted on the basis of climatic niche, and does not consider other potential variables affecting the ecological niche of the species. The most relevant factor potentially making the future scenario much worse than those modelled on the basis of predicted climate is represented by the availability of habitat. This species is strongly linked to open habitats, often with traditional management (Gestri et al. 2010), but these habitats are disappearing in most of the hills and submontane ecosystems of peninsular Italy because of socio-economic changes and of the concentration of population in lower elevation areas (Falcucci et al. 2007). Forest communities are occupying previously grazed or cultivated lands in the higher hills and lower mountains (see e.g., Geri et al. 2010; Amici et al. 2013), promoting more natural habitat types but affecting the persistence of species linked to secondary and cultural landscapes (Amici et al. 2015).

In addition to habitat loss, the limited dispersal ability is a further factor which should be considered to assess the actual extinction threat of *B. webbia*. Indeed, given its relatively large seeds (Astuti et al. 2018), the dispersal capacity of this species may be insufficient to cope with the speed needed for the upslope shift requested by the climate change. Then, even admitting that potentially suitable areas at higher elevations could effectively host *B. webbia* and that this species could colonise these areas by natural or assisted migration (Brodie et al. 2021), then this would imply an increasing connection between the two currently disjunct population groups. This increasing connection would, in turn, promote a potential loss of the genetic and functional differentiation documented for some populations (Astuti et al. 2018, 2019; Peruzzi et al. 2021). Moreover, considering that the actual AOO documented for *Bellevalia webbia* amounts to just 47 2×2 km cells (of which only 24 were confirmed in recent times) and that forest expansion in Apennine mountains could further reduce the availability of open habitats (Gargano et al. 2012), this species shows evident conservation concerns. To overcome these problems, in addition to assisted colonization (Casazza et al. 2021), a proper *ex situ* conservation programme should be planned, as an insurance policy against extinction (Li and Pritchard 2009).

References

- Amici V, Santi E, Filibeck G, Diekmann M, Geri F, Landi S, Scoppola A, Chiarucci A (2013) Influence of secondary forest succession on plant diversity patterns in a Mediterranean landscape. *Journal of Biogeography* 40(12): 2335–2347. <https://doi.org/10.1111/jbi.12182>
- Amici V, Landi S, Frascaroli F, Rocchini D, Santi E, Chiarucci A (2015) Anthropogenic drivers of plant diversity: Perspective on land use change in a dynamic cultural landscape. *Biodiversity and Conservation* 24(13): 3185–3199. <https://doi.org/10.1007/s10531-015-0949-x>
- Araújo MB, New M (2007) Ensemble forecasting of species distributions. *Trends in Ecology & Evolution* 22(1): 42–47. <https://doi.org/10.1016/j.tree.2006.09.010>

- Assis J, Araújo MB, Serrão EA (2018) Projected climate changes threaten ancient refugia of kelp forests in the North Atlantic. *Global Change Biology* 24(1): e55–e66. <https://doi.org/10.1111/gcb.13818>
- Astuti G, Brullo S, Domina G, El Mokni R, Giordani T, Peruzzi L (2017) Phylogenetic relationships among tetraploid species of *Bellevalia* (Asparagaceae) endemic to south central Mediterranean. *Plant Biosystems* 151(6): 1120–1128. <https://doi.org/10.1080/11263504.2017.1320308>
- Astuti G, Bedini G, Carta A, Roma-Marzio F, Trinco A, Peruzzi L (2018) Comparative assessment of reproductive traits across different habitats in the endangered Webb's hyacinth (*Bellevalia webbiana* Parl.). *Nature Conservation* 24: 81–92. <https://doi.org/10.3897/natureconservation.24.20650>
- Astuti G, Ciccarelli D, Roma-Marzio F, Trinco A, Peruzzi L (2019) Narrow endemic species *Bellevalia webbiana* shows significant intraspecific variation in tertiary CSR strategy. *Plant Biosystems* 153(1): 12–18. <https://doi.org/10.1080/11263504.2018.1435576>
- Barbet-Massin M, Jetz W (2014) A 40-year, continent-wide, multispecies assessment of relevant climate predictors for species distribution modelling. *Diversity & Distributions* 20(11): 1285–1295. <https://doi.org/10.1111/ddi.12229>
- Bartolucci F, Peruzzi L, Galasso G, Albano A, Alessandrini A, Ardenghi NMG, Astuti G, Bacchetta G, Ballelli S, Banfi E, Barberis G, Bernardo L, Bouvet D, Bovio M, Cecchi L, Di Pietro R, Domina G, Fascetti S, Fenu G, Festi F, Foggi B, Gallo L, Gubellini L, Gottschlich G, Iamónico D, Iberite M, Jinénez-Mejías P, Lattanzi E, Martinetto E, Masin RR, Medagli P, Passalacqua NG, Peccenini S, Pennesi R, Pierini B, Poldini L, Prosser F, Raimondo FM, Marchetti D, Roma-Marzio F, Rosati L, Santangelo A, Scoppola A, Scortegagna S, Selvaggi A, Selvi F, Soldano A, Stinca A, Wagensommer RP, Wilhalm T, Conti F (2018) An updated checklist of the vascular flora native to Italy. *Plant Biosystems* 152(2): 179–303. <https://doi.org/10.1080/11263504.2017.1419996>
- Bartolucci F, Galasso G, Peruzzi L, Conti F (2022) Report 2021 on plant biodiversity in Italy: Native and alien vascular flora. *Natural History Sciences* 8(1): 41–54. <https://doi.org/10.4081/nhs.2022.623>
- Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. *Ecology Letters* 15(4): 365–377. <https://doi.org/10.1111/j.1461-0248.2011.01736.x>
- Borzatti von Loewenstern A, Giordani T, Astuti G, Andreucci A, Peruzzi L (2013) Phylogenetic relationship of Italian *Bellevalia* species (Asparagaceae), inferred from morphology, karyology and molecular systematics. *Plant Biosystems* 147(3): 776–787. <https://doi.org/10.1080/11263504.2013.829884>
- Boucher O, Servonnat J, Albright AL, Aumont O, Balkanski Y, Bastrikov V, Bekki S, Bonnet R, Bony S, Bopp L, Braconnot P, Brockmann P, Cadule P, Caubel A, Cheruy F, Codron F, Cozic A, Cugnet D, D'Andrea F, Davini P, de Lavergne C, Denvil S, Deshayes J, Devilliers M, Ducharne A, Dufresne J-L, Dupont E, Éthé C, Fairhead L, Falletti L, Flavoni S, Foujols M-A, Gardoll S, Gastineau G, Ghattas J, Grandpeix J-Y, Guenet B, Guez LE, Guilyardi E, Guimberteau M, Hauglustaine D, Hourdin F, Idelkadi A, Joussaume S, Kageyama M, Khodri M, Krinner G, Lebas N, Levavasseur G, Lévy C, Li L, Lott F, Lurton T, Luyssaert S, Madec G, Madeleine J-B, Maignan F, Marchand M, Marti O, Mellul L, Meurdesoif Y, Mignot J, Musat I, Ottlé C, Peylin P, Planton Y, Polcher J, Rio

- C, Rochetin N, Rousset C, Sepulchre P, Sima A, Swingedouw D, Thiéblemont R, Traore AK, Vancoppenolle M, Vial J, Vialard J, Viovy N, Vuichard N (2020) Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems* 12: e2019MS002010. <https://doi.org/10.1029/2019MS002010>
- Brodie F, Lieberman S, Moehrensclager A, Redford KH, Rodríguez JP, Schwartz M, Seddon PJ, Watson JEM (2021) Global policy for assisted colonization of species. *Science* 372(6541): 456–458. <https://doi.org/10.1126/science.abg0532>
- Casazza G, Giordani P, Benesperi R, Foggi B, Viciani D, Filigheddu R, Farris E, Bagella S, Pisanu S, Mariotti MG (2014) Climate change hastens the urgency of conservation for range-restricted plant species in the central-northern Mediterranean region. *Biological Conservation* 179: 129–138. <https://doi.org/10.1016/j.biocon.2014.09.015>
- Casazza G, Abeli T, Bacchetta G, Dagnino D, Fenu G, Gargano D, Minuto L, Montagnani C, Orsenigo S, Peruzzi L, Varaldo L, Rossi G (2021) Combining conservation status and species distribution models for planning assisted colonisation under climate change scenario. *Journal of Ecology* 109(6): 2284–2295. <https://doi.org/10.1111/1365-2745.13606>
- Chen X, Dimitrov NB, Meyers LA (2019) Uncertainty analysis of species distribution models. *PLoS ONE* 14(5): e0214190. <https://doi.org/10.1371/journal.pone.0214190>
- Chiarugi A (1949) Saggio di una revisione cito-sistematica della flora italiana I Il tetraploidismo della *Bellevalia webbiana* Parl e il suo diritto di cittadinanza nella flora italiana. *Caryologia* 1(3): 362–376. <https://doi.org/10.1080/00087114.1949.10797519>
- Corlett RT (2016) Plant diversity in a changing world: Status, trends, and conservation needs. *Plant Diversity* 38(1): 10–16. <https://doi.org/10.1016/j.pld.2016.01.001>
- Corlett RT (2020) Safeguarding our future by protecting biodiversity. *Plant Diversity* 42(4): 221–228. <https://doi.org/10.1016/j.pld.2020.04.002>
- Darrah SE, Bland LM, Bachman SP, Clubbe CP, Trias-Blasi A (2017) Using coarse-scale species distribution data to predict extinction risk in plants. *Diversity & Distributions* 23(4): 435–447. <https://doi.org/10.1111/ddi.12532>
- Dirnböck T, Essl F, Rabitsch W (2011) Disproportional risk for habitat loss of high-altitude endemic species under climate change. *Global Change Biology* 17(2): 990–996. <https://doi.org/10.1111/j.1365-2486.2010.02266.x>
- Dolci D, Peruzzi L (2022) Assessing the effectiveness of correlative ecological niche models temporal projection through floristic data. *Biology (Basel)* 11(8): 1219. <https://doi.org/10.3390/biology11081219>
- Dülgeroğlu C, Aksoy A (2019) Assessing impacts of climate change on *Campanula yaltirikii* H.Duman (Campanulaceae), a critically endangered endemic species in Turkey. *Turkish Journal of Botany* 43(2): 243–252. <https://doi.org/10.3906/bot-1809-14>
- Engler R, Randin CF, Thuiller W, Dullinger S, Zimmermann NE, Araújo MB, Pearman PB, Le Lay G, Piedallu C, Albert CH, Choler P, Coldea G, De Lamo X, Dirnböck T, Gégout J-C, Gómez-García D, Grytnes J-A, Heegaard E, Høistad F, Nogués-Bravo D, Normand S, Puşcaş M, Sebastià M-T, Stanisci A, Theurillat J-P, Trivedi MR, Vittoz P, Guisan A (2011) 21st century climate change threatens mountain flora unequally across Europe. *Global Change Biology* 17(7): 2330–2341. <https://doi.org/10.1111/j.1365-2486.2010.02393.x>

- Falcucci A, Maiorano L, Boitani L (2007) Changes in land-use/land-cover patterns in Italy and their implications for biodiversity conservation. *Landscape Ecology* 22(4): 617–631. <https://doi.org/10.1007/s10980-006-9056-4>
- Feng G, Huang X, Mao L, Wang N, Yang X, Wang Y (2020) More endemic birds occur in regions with stable climate, more plant species and high altitudinal range in China. *Avian Research* 11(1): 1–8. <https://doi.org/10.1186/s40657-020-00203-y>
- Freedman DA (1981) Bootstrapping regression models. *Annals of Statistics* 9(6): 1218–1228. <https://doi.org/10.1214/aos/1176345638>
- Gargano D, Mingozi A, Massolo A, Rinaldo S, Bernardo L (2012) Patterns of vegetation cover/dynamics in a protected Mediterranean mountain area: Influence of the ecological context and protection policy. *Plant Biosystems* 146: 9–18. <https://doi.org/10.1080/11263504.2011.641689>
- Geri F, Rocchini D, Chiarucci A (2010) Landscape metrics and topographical determinants of large-scale forest dynamics in a Mediterranean landscape. *Landscape and Urban Planning* 95(1–2): 46–53. <https://doi.org/10.1016/j.landurbplan.2009.12.001>
- Gestri G, Alessandrini A, Sirotti N, Carta A, Peruzzi L (2010) Contributo alla conoscenza della flora vascolare endemica di Toscana ed aree contermini 2 *Bellevalia webbiana* Parl (Asparagaceae). *Informatore Botanico Italiano* 42: 449–455.
- Greenwell BM, Boehmke BC, McCarthy AJ (2018) A simple and effective model-based variable importance measure. arXiv preprint arXiv: 1805.04755.
- He X, Burgess KS, Yang XF, Ahrends A, Gao LM, Li DZ (2019) Upward elevation and north-west range shifts for alpine *Meconopsis* species in the Himalaya-Hengduan Mountains region. *Ecology and Evolution* 9(7): 4055–4064. <https://doi.org/10.1002/ece3.5034>
- Hijmans RJ, Phillips S, Leathwick J, Elith J, Hijmans MRJ (2017) Package ‘dismo’. *Circles* 9(1): 1–68.
- Hirzel AH, Le Lay G, Helfer V, Randin C, Guisan A (2006) Evaluating the ability of habitat suitability models to predict species presences. *Ecological Modelling* 199(2): 142–152. <https://doi.org/10.1016/j.ecolmodel.2006.05.017>
- Hong-Wa C, Arroyo TPF (2012) Climate-induced range contraction in the Malagasy endemic plant genera *Mediusella* and *Xerochlamys* (Sarcocaulaceae). *Plant Ecology and Evolution* 145(3): 302–312. <https://doi.org/10.5091/plecevo.2012.742>
- IUCN Standards and Petitions Committee (2022) Guidelines for using the IUCN Red List Categories and Criteria. Version 15.1. Prepared by the Standards and Petitions Committee, 1–114. https://nc.iucnredlist.org/redlist/content/attachment_files/RedListGuidelines.pdf [accessed 28 July 2022]
- Karger DN, Conrad O, Böhner J, Kawohl T, Kreft H, Soria-Auza RW, Zimmermann NE, Linder P, Kessler M (2021) Climatologies at high resolution for the earth's land surface areas. *EnviDat*. <https://doi.org/10.16904/envidat.228.v2.1>
- Khajoei Nasab F, Mehrabian A, Mostafavi H (2020) Mapping the current and future distributions of *Onosma* species endemic to Iran. *Journal of Arid Land* 12(6): 1031–1045. <https://doi.org/10.1007/s40333-020-0080-z>
- Khanum R, Mumtaz AS, Kumar S (2013) Predicting impacts of climate change on medicinal asclepiads of Pakistan using Maxent modeling. *Acta Oecologica* 49: 23–31. <https://doi.org/10.1016/j.actao.2013.02.007>

- Li D-Z, Pritchard HW (2009) The science and economics of ex situ plant conservation. *Trends in Plant Science* 14(11): 614–621. <https://doi.org/10.1016/j.tplants.2009.09.005>
- Liu C, Berry PM, Dawson TP, Pearson RG (2005) Selecting thresholds of occurrence in the prediction of species distributions. *Ecography* 28(3): 385–393. <https://doi.org/10.1111/j.0906-7590.2005.03957.x>
- Lobo JM, Jiménez-Valverde A, Real R (2008) AUC: A misleading measure of the performance of predictive distribution models. *Global Ecology and Biogeography* 17(2): 145–151. <https://doi.org/10.1111/j.1466-8238.2007.00358.x>
- Merow C, Smith MJ, Silander Jr JA (2013) A practical guide to MaxEnt for modeling species' distributions: What it does, and why inputs and settings matter. *Ecography* 36(10): 1058–1069. <https://doi.org/10.1111/j.1600-0587.2013.07872.x>
- Morueta-Holme N, Engemann K, Sandoval-Acuña P, Jonas JD, Segnitz RM, Svenning J (2015) Strong upslope shifts in Chimborazo's vegetation over two centuries since Humboldt. *Proceedings of the National Academy of Sciences of the United States of America* 112(41): 12741–12745. <https://doi.org/10.1073/pnas.1509938112>
- Orsenigo S, Montagnani C, Fenu G, Gargano D, Peruzzi L, Abeli T, Alessandrini A, Bacchetta G, Bartolucci F, Bovio M, Brullo C, Brullo S, Carta A, Castello M, Cogoni D, Conti F, Domina G, Foggi B, Gennai M, Gigante D, Iberite M, Lasen C, Magrini S, Perrino EV, Prosser F, Santangelo A, Selvaggi A, Stinca A, Vagge I, Villani M, Wagensommer RP, Wilhalm T, Tartaglini N, Duprè E, Blasi C, Rossi G (2018) Red Listing plants under full national responsibility: Extinction risks and threats in the vascular flora endemic to Italy. *Biological Conservation* 224: 213–222. <https://doi.org/10.1016/j.biocon.2018.05.030>
- Owens HL, Campbell LP, Dornak LL, Saupe EE, Barve N, Soberón J, Ingenloff K, Lira-Noriega A, Hensz CM, Myers CE, Peterson AT (2013) Constraints on interpretation of ecological niche models by limited environmental ranges on calibration areas. *Ecological Modelling* 263: 10–18. <https://doi.org/10.1016/j.ecolmodel.2013.04.011>
- Peruzzi L, Carta A (2011) *Bellevalia webbia*. The IUCN Red List of Threatened Species 2011: eT195349A8957996. <http://dxdoiorg/102305/IUCN2011-2RLTST195349A8957996en>
- Peruzzi L, Conti F, Bartolucci F (2014) An inventory of vascular plants endemic to Italy. *Phytotaxa* 168(1): 1–75. <https://doi.org/10.11646/phytotaxa.168.1.1>
- Peruzzi L, Domina G, Bartolucci F, Galasso G, Peccenini S, Raimondo FM, Albano A, Alessandrini A, Banfi E, Barberis G, Bernardo L, Bovio M, Brullo S, Brundu G, Brunu A, Camarda I, Carta L, Conti F, Croce A, Iamónico D, Iberite M, Iiriti G, Longo D, Marsili S, Medagli P, Pistarino A, Salmeri C, Santangelo A, Scassellati E, Selvi F, Soldano A, Stinca A, Villani M, Wagensommer RP, Passalacqua NG (2015) An inventory of the names of vascular plants endemic to Italy, their loci classici and types. *Phytotaxa* 196(1): 1–217. <https://doi.org/10.11646/phytotaxa.196.1.1>
- Peruzzi L, Roma-Marzio F, Pinzani L, Bedini G (2019 onwards) Wikiplantbase #Italia. <http://bot.biologia.unipi.it/wpb/italia/index.html> [accessed 22 June 2022]
- Peruzzi L, Astuti G, Algisi S, Coppi A (2021) Genetic differentiation among populations of the threatened *Bellevalia webbia* (Asparagaceae) and its consequence on conservation. *Plant Biosystems* 155(1): 188–193. <https://doi.org/10.1080/11263504.2020.1857866>

- Peterson AT, Samy AM (2016) Geographic potential of disease caused by Ebola and Marburg viruses in Africa. *Acta Tropica* 162: 114–124. <https://doi.org/10.1016/j.actatropica.2016.06.012>
- Phillips SJ, Anderson RP, Dudík M, Schapire RE (2022) Maxent software for modeling species niches and distributions (Version 3.4.4). http://biodiversityinformatics.amnh.org/open_source/maxent/ [accessed 1 June 2022]
- Randin CF, Engler R, Normand S, Zappa M, Zimmermann NE, Pearman PB, Vittoz P, Thuiller W, Guisan A (2009) Climate change and plant distribution: Local models predict high-elevation persistence. *Global Change Biology* 15(6): 1557–1569. <https://doi.org/10.1111/j.1365-2486.2008.01766.x>
- Scholbeck CA, Molnar C, Heumann C, Bischl B, Casalicchio G (2019) Sampling, intervention, prediction, aggregation: a generalized framework for model-agnostic interpretations. *Joint European Conference on Machine Learning and Knowledge Discovery in Databases*. Springer, Cham, 205–216. https://doi.org/10.1007/978-3-030-43823-4_18
- Semu AA, Bekele T, Lulekal E, Cariñanos P, Nemomissa S (2021) Projected impact of climate change on habitat suitability of a vulnerable endemic *Vachellia negrii* (Pic.Serm.) Kyal. & Boatwr. (Fabaceae) in Ethiopia. *Sustainability (Basel)* 13(20): e 11275. <https://doi.org/10.3390/su132011275>
- Steinbauer MJ, Grytnes J-A, Jurasinski G, Kulonen A, Lenoir J, Pauli H, Rixen C, Winkler M, Bardy-Durchhalter M, Barni E, Bjorkman AD, Breiner FT, Burg S, Czortek P, Dawes MA, Delimat A, Dullinger S, Erschbamer B, Felde VA, Fernández-Arberas O, Fossheim KF, Gómez-García D, Georges D, Grindrud ET, Haider S, Haugum SV, Henriksen H, Herreiros MJ, Jaroszewicz B, Jaroszynska F, Kanka R, Kapfer J, Klanderud K, Kühn I, Lamprecht A, Matteodo M, Morra di Cella U, Normand S, Odland A, Olsen SL, Palacio S, Petey M, Piscová V, Sedlakova B, Steinbauer K, Stöckli V, Svenning J-C, Teppa G, Theurillat J-P, Vittoz P, Woodin SJ, Zimmermann NE, Wipf S (2018) Accelerated increase in plant species richness on mountain summits is linked to warming. *Nature* 556(7700): 231–234. <https://doi.org/10.1038/s41586-018-0005-6>
- Title PO, Bemmels JB (2018) ENVIREM: An expanded set of bioclimatic and topographic variables increases flexibility and improves performance of ecological niche modeling. *Ecography* 41(2): 291–307. <https://doi.org/10.1111/ecog.02880>
- Walker S (2014) Applying extinction risk modelling to develop global conservation priorities for bulbous monocots. Doctoral dissertation, Department of Life Sciences, Silwood Park, Imperial College London, 1–66.
- Warren DL, Matzke NJ, Cardillo M, Baumgartner JB, Beaumont LJ, Turelli M, Glor RE, Huron NA, Simões M, Iglesias TL, Piquet JC, Dinnage R (2021) ENMTools 1.0: An R package for comparative ecological biogeography. *Ecography* 44(4): 504–511. <https://doi.org/10.1111/ecog.05485>
- Wulff AS, Hollingsworth PM, Ahrends A, Jaffré T, Veillon JM, L'Huillier L, Fogliani B (2013) Conservation priorities in a biodiversity hotspot: Analysis of narrow endemic plant species in New Caledonia. *PLoS ONE* 8(9): e73371. <https://doi.org/10.1371/journal.pone.0073371>